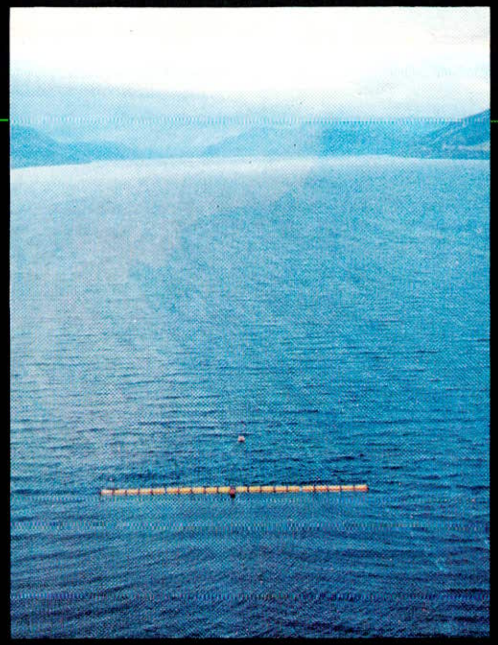
SEA Clam Wave Energy Converter

SEA-Lanchester
WAVE ENERGY



Aerial view of Loch Ness 1/10th scale wave energy tests.

Force 10 gale at Loch Ness gives waves equivalent to 30m at full scale.

1/10 scale bag-turbine-alternator rig under test at Coventry (Lanchester) Polytechnic.

Offshore loading tower under construction by Fairclough associate company Howard Doris Ltd at their Kishorn base, Northern Scotland. The SEA Clam will require similar construction facilities.

1/50th scale Clam tests in a laboratory wave channel at the Polytechnic.

What are the advantages?

Although conditions under which wave energy converters have to operate can be extremely severe, they are expected to remain unattended and on station for long periods. The Clam acknowledges the environment by being robust and simple. Each Clam element has only two moving parts, the bag and the turbo-generator rotor, both of which are inherently reliable.

The proposed power transmission fluid is air. Of the three fluids available for wave power devices – air, water and oil – air is generally accepted as the most desirable. The Clam has an additional advantage in that the air is used in closed circuit, thus eliminating the risk of equipment damage from sea water entrainment.

Although wave energy is a free and renewable resource, high capital costs are incurred by wave energy converters by virtue of their large size. Cost effectiveness of the Clam is achieved through the use of the long floating spine which maximises energy capture whilst obviating the need to resist the immense forces experienced by a fixed structure in storm conditions. The spine, simpler than any other proposed in the UK wave energy programme, acts as a stable support for bags and turbo-generators and houses no complex equipment. The high power rating of the Clam minimises the total number of moored units and allows efficient use of the coastline, whilst its simple power conversion system leads directly to lower capital and running costs.

The SEA Clam has been designed to operate in the severe Atlantic conditions off the coast of the Hebrides, but is adaptable to a wide range of sea states and operational locations around the world.

What will the power cost?

Assessments of wave energy converter systems are carried out by the consultants Rendel, Palmer & Tritton and Kennedy & Donkin in conjunction with the Department of Energy. In 1979 the first Clam design was assessed as able to produce power at 6p/kWh. The new design is being rigorously assessed in 1981 and present evidence indicates that the cost of power delivered will be around 4 to 6p/kWh at 1981 prices. This shows that the steady development of wave energy technology is improving costs particularly when it is noted that electricity prices have risen by over 40% between the assessments.

Present indications are that when the Clam is developed to its full potential the cost of power generated should be 3 to 4p/kWh.

The next step

Wave energy has to be demonstrated by a prototype at near full scale. Testing at small scale is useful in a research sense but will not prove the viability of wave power as an energy resource. Sufficient knowledge has been gained over the past five years to enable a promising design to be tested at a scale which will prove its engineering credibility and cost effectiveness.

The SEA Clam development has reached a stage where a full scale device could be built with confidence.

Clam Specification

Each Device Unit	
Length	275 m
Depth	15 m
Width	13 m
Displacement	44,000 tonne
Maximum power rating	10 MW

2 GW Station	
No. of devices	320
Length of coastline	130 km
Available average power	50 kW/m
Average annual output	0.65 GW
Maximum rated output	2 GW
Estimated Capital Cost	£3000 M
Annual capital charges	£210 M
Annual operating cost	£50 M
Cost per kWh generated	5p

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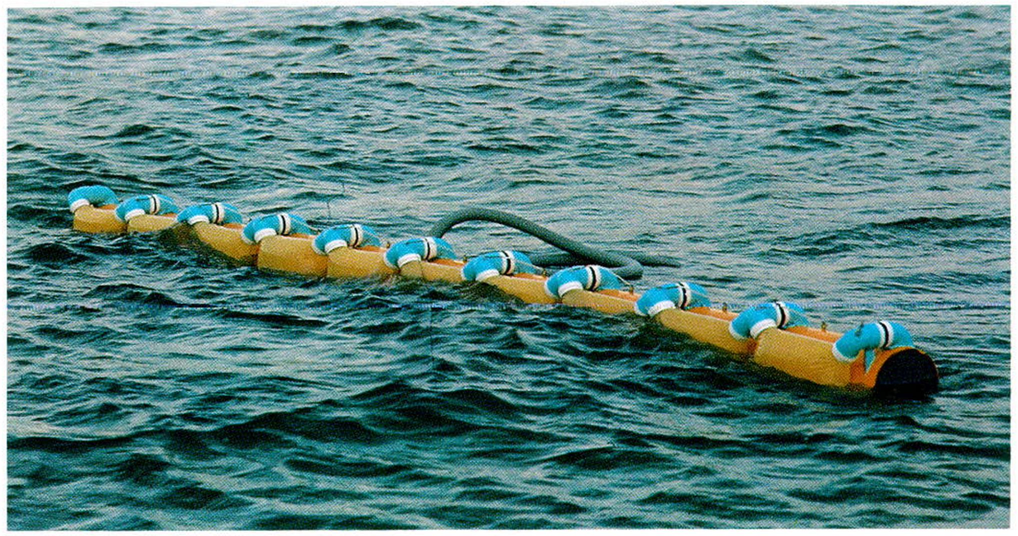
The SEA Clam Wave Energy Converter

The SEA Clam is a simple device which utilises the displacement of air to extract energy from sea waves. Flexible air bags attached to the face of a floating spine breathe in response to wave forces. This causes air to be forced through self-rectifying turbines into and out of the hollow spine, allowing interchange of air between Clam bags. The randomness of sea wave patterns allows phased operation of the Clam elements, enabling the spine to act as a stable reference body. Typically a 10 MW generating unit would feature ten Clam elements on a 275 m long spine, moored at an angle to the waves, as illustrated on the cover.



1/50th scale SEA Clam tests at Draycote reservoir, near Rugby.

How did it evolve?

The SEA-Lanchester team has been involved in wave energy research since the inception of the national programme in 1975. It is one of only two groups in the U.K. who have been outside the laboratory and designed, built and tested a working model of a wave power device at an engineering scale in real waves. This was a 'first generation' device tested at 1/10th scale at Loch Ness. Further 1/10th scale work on the 'second generation' Clam and supporting full scale design studies have placed SEA-Lanchester in a unique position to identify and pursue the most fruitful lines of investigation and development. The Clam is the result of more than six years of testing, analysis and experience.

State of development

The SEA Clam concept has been developed over the last four years towards a full scale reference design which can be assessed for credibility and cost. Each component part has been designed in detail by the Lanchester group working in conjunction with members of the SEA consortium and other industrial companies. This has instilled confidence in the current design of the four principal components which make up the Clam: air bags, spine, turbo-generators and moorings.

To support the full scale design studies each component has been tested at large scale:

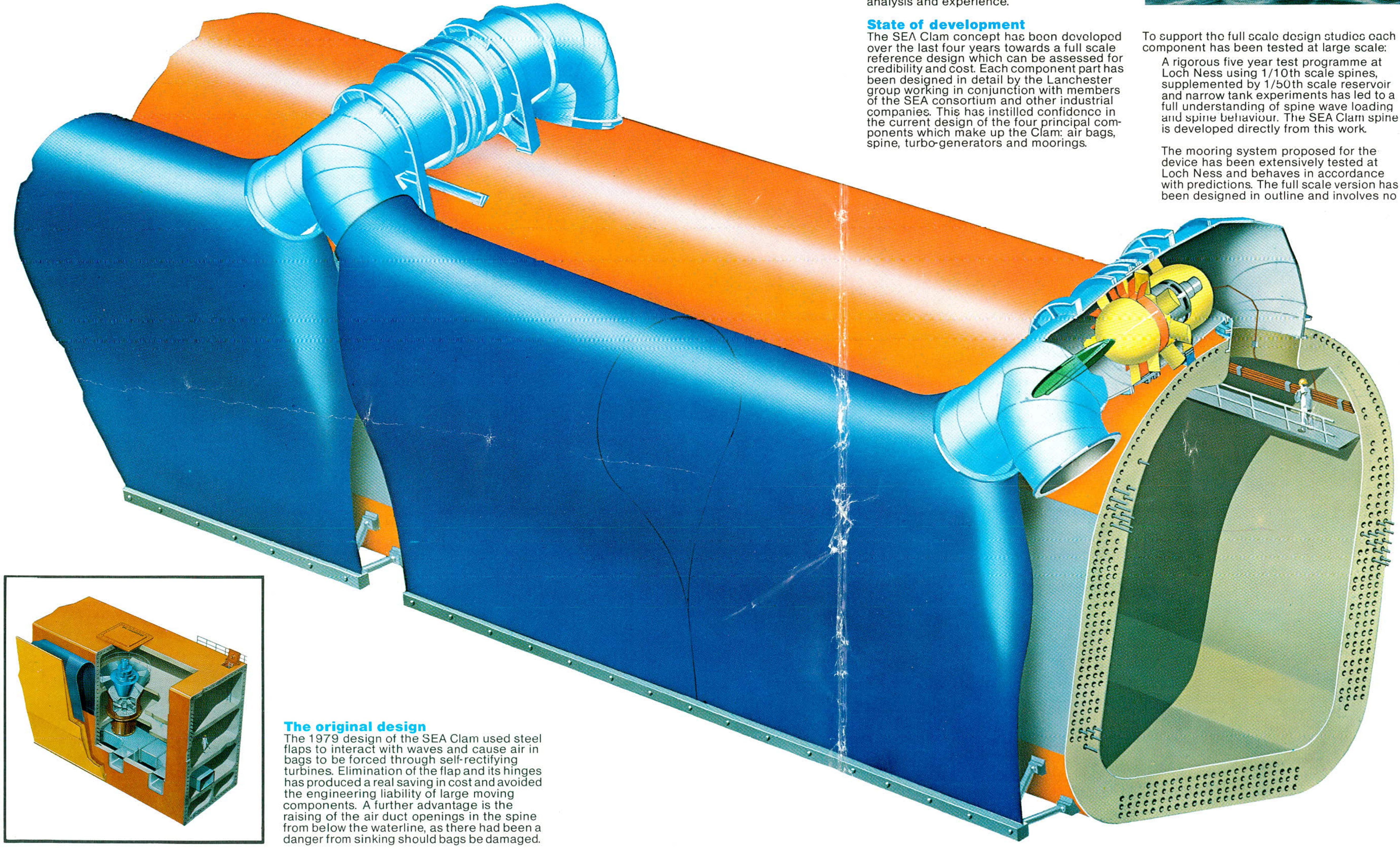
A rigorous five year test programme at Loch Ness using 1/10th scale spines, supplemented by 1/50th scale reservoir and narrow tank experiments has led to a full understanding of spine wave loading and spine behaviour. The SEA Clam spine is developed directly from this work.

The mooring system proposed for the device has been extensively tested at Loch Ness and behaves in accordance with predictions. The full scale version has been designed in outline and involves no unproven technology. Mooring requirements are fully understood and calculable.

The self-rectifying turbine proposed for use in the device has been tested at 1/10th scale in representative fluctuating air flow using a purpose built bag-turbine-alternator rig at Lanchester. The turbine offers efficient operation in line with theoretical analysis, and is ideal for the wave energy application. Its inherent linear damping characteristic ensures efficient energy capture over the wide range of sea states encountered in the Atlantic.

The air bags are to be constructed from Kevlar reinforced fabric. Kevlar is a new tyre cord renowned for its strength and long flexural life. Studies by fabric experts coupled with information from a bag testing programme indicate that bags with a long working life can be designed.

Tests on a small scale model in a wide wave tank have established the wave to air power performance of the Clam in a range of sea states which represent the Atlantic wave spectrum. A larger 1/10th scale model is currently being tested in Loch Ness and is expected to given an improved performance by virtue of its more representative scale and lower model losses. The SEA Clam development is backed by the national wave energy programme which has supported many generic studies having a bearing on Clam design.



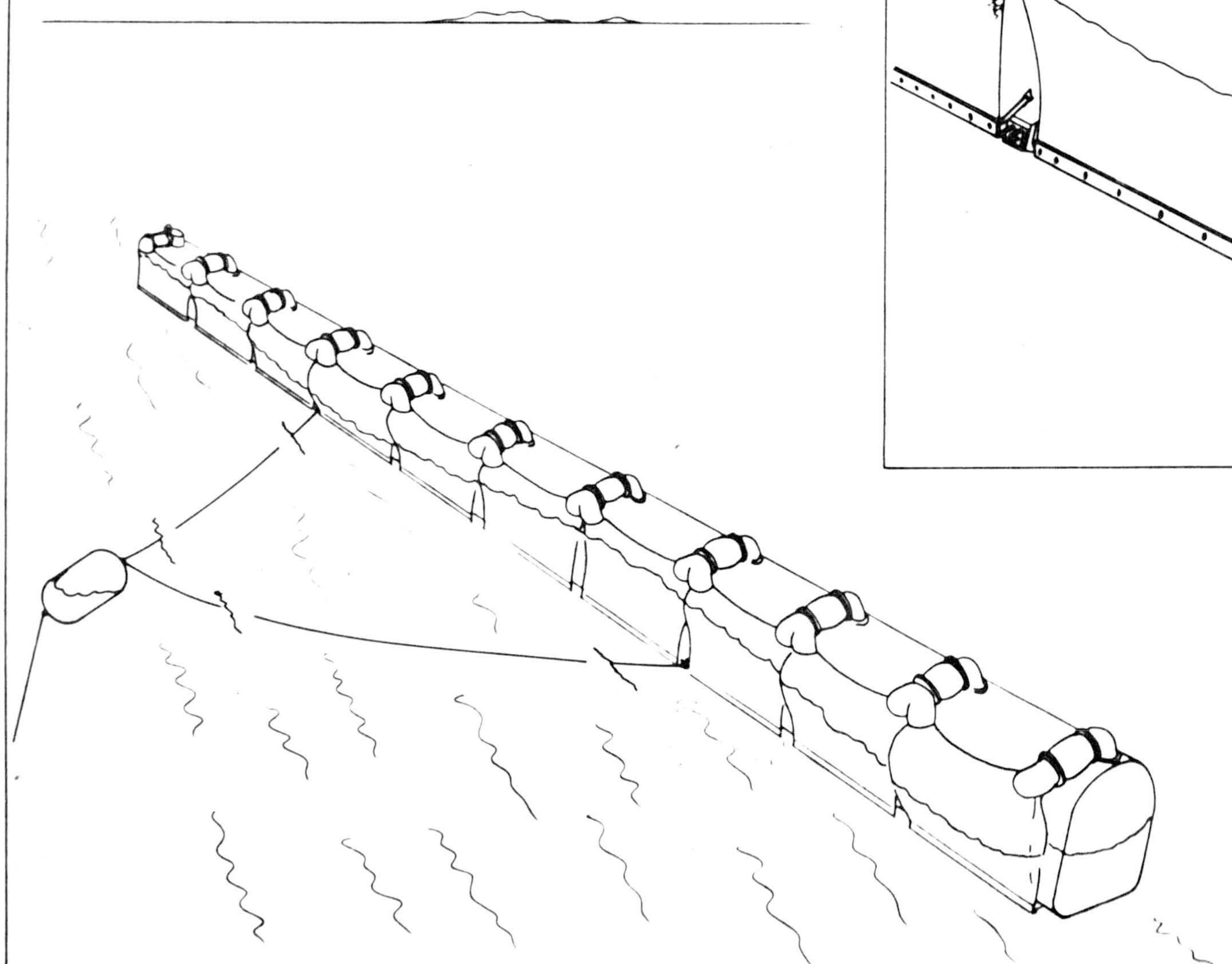
The original design

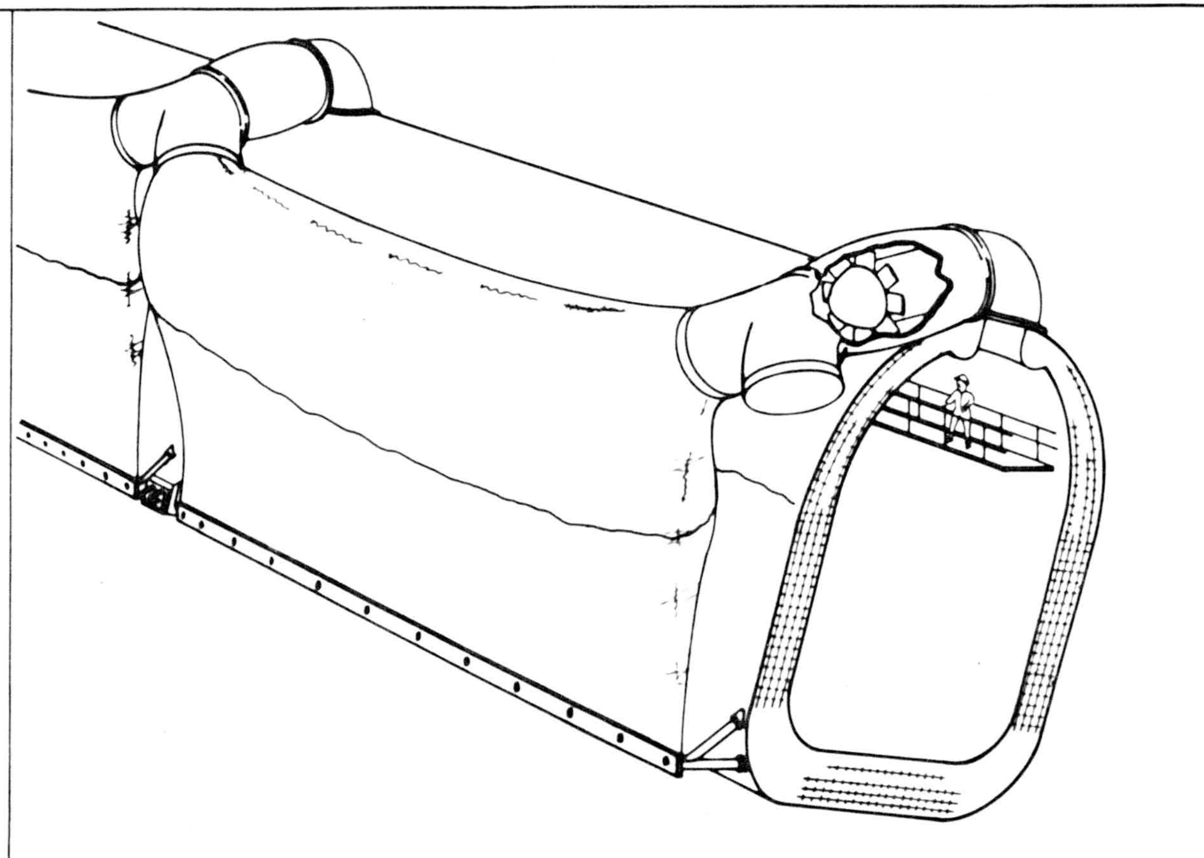
The 1979 design of the SEA Clam used steel flaps to interact with waves and cause air in bags to be forced through self-rectifying turbines. Elimination of the flap and its hinges has produced a real saving in cost and avoided the engineering liability of large moving components. A further advantage is the raising of the air duct openings in the spine from below the waterline, as there had been a danger from sinking should bags be damaged.

Who is backing it?

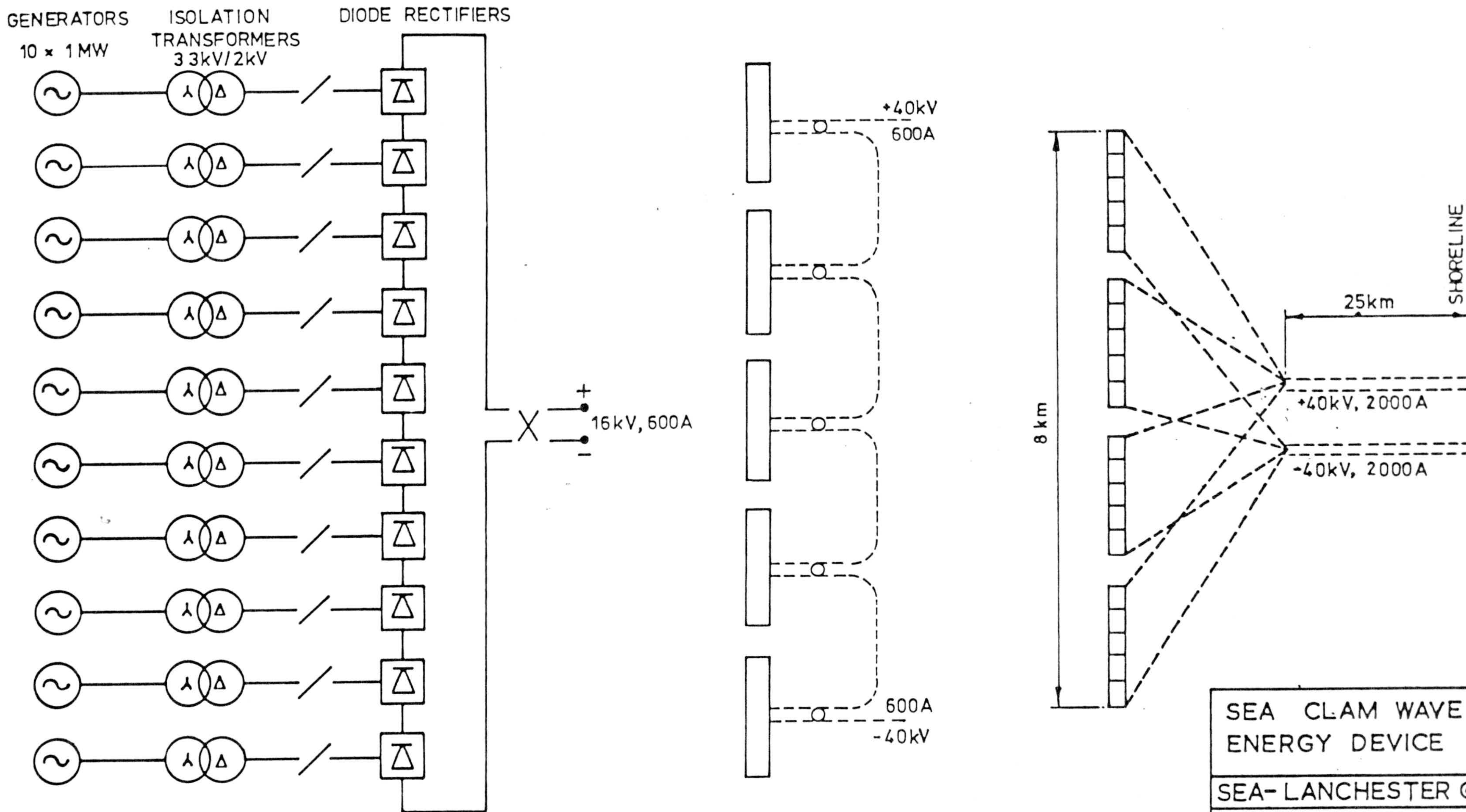
Research into the device has been funded by the Department of Energy, and also by Sea Energy Associates Ltd – a company originally formed by a consortium between R.M.C. Group p.l.c., Cawoods Ltd and inventors working in wave energy. Subsequently the consortium has been joined by Fairclough Construction Group p.l.c. who, in conjunction with their associated company Howard Doris Ltd, have contributed their unrivalled expertise in civil engineering, structural steel work, and off-shore construction to the project.

SEA Ltd are continuing to provide financial backing to the SEA Clam because they believe that it offers the most realistic and economic solution yet devised for extracting useful energy from sea waves.





SEA CLAM WAVE ENERGY DEVICE	
SEA-LANCHESTER ©	
TITLE	PERSPECTIVE VIEW
FIG N°	
DRAWN	RD & ES
DATE	OCTOBER 81



SPINE ELECTRICAL PLANT

48 MW SERIES GROUP

150 MW 'PARALLEL' GROUP

SEA CLAM WAVE ENERGY DEVICE	
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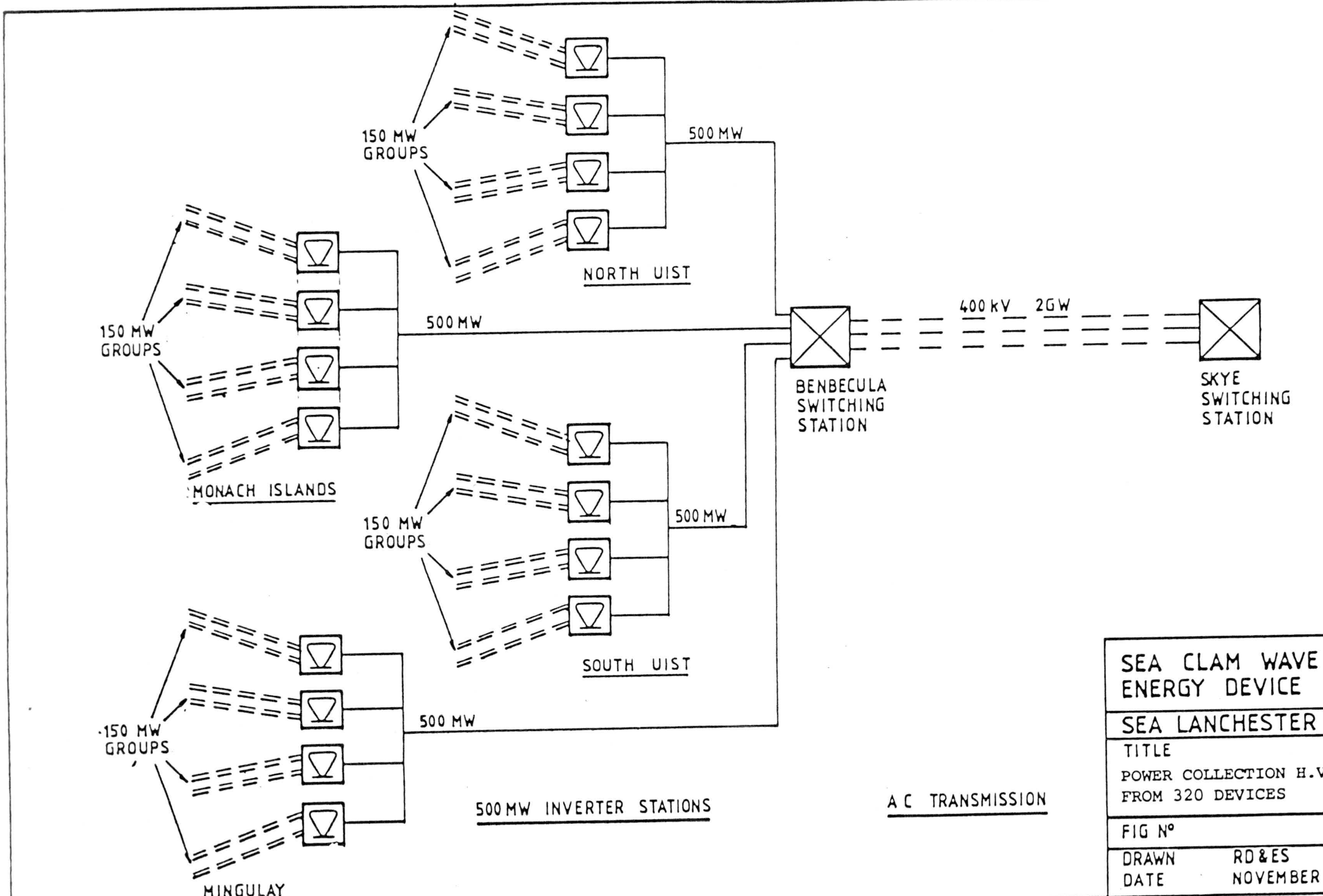
TITLE	
POWER COLLECTION MVDC FROM 20 DEVICES	
FIG No.	
DRAWN	RD & ES
DATE	OCTOBER '81



SEA CLAM WAVE ENERGY DEVICE

SEA LANCHESTER ©

TITLE

POWER COLLECTION H.V.A.C FROM 320 DEVICES

FIG N°

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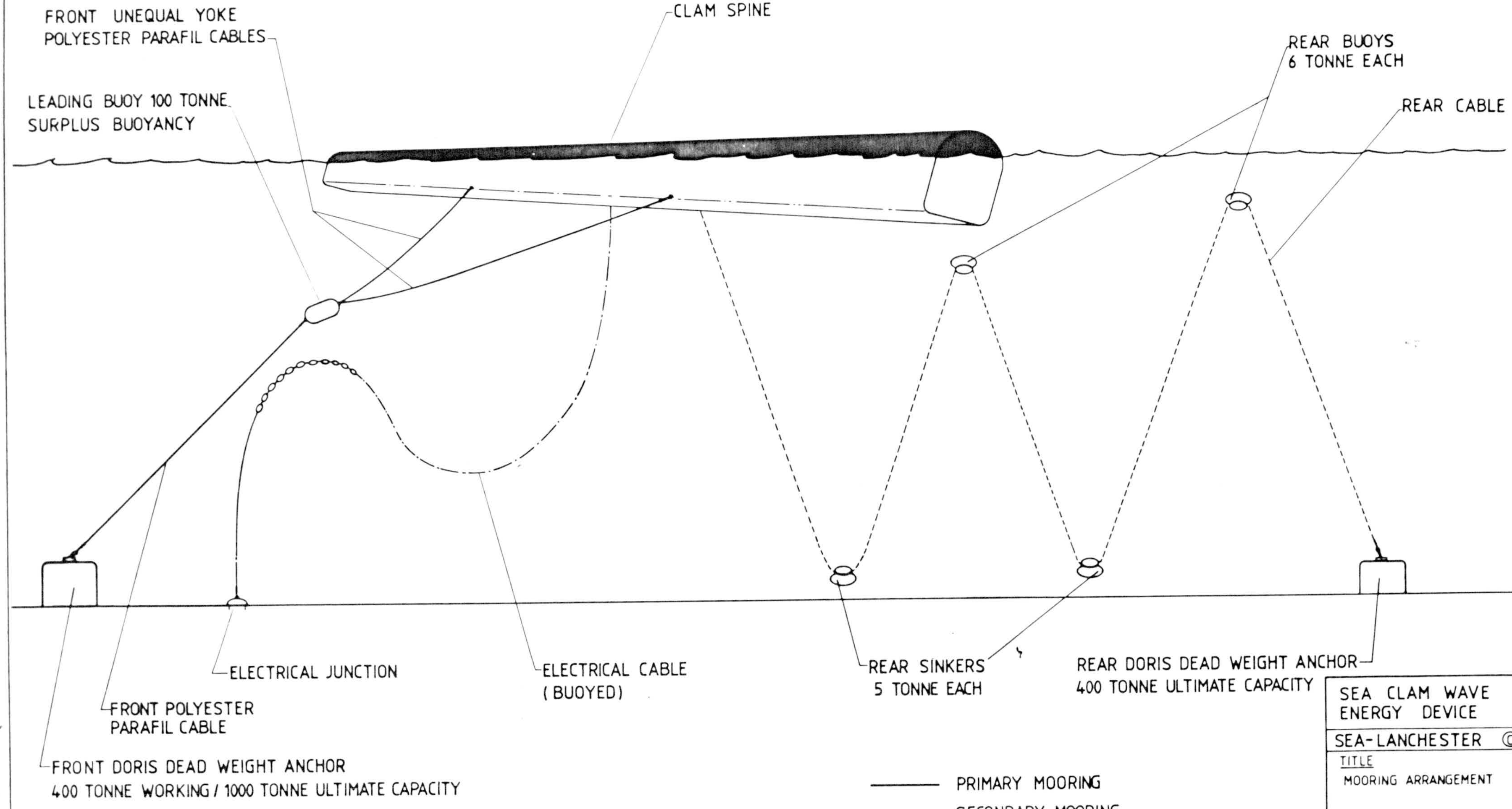

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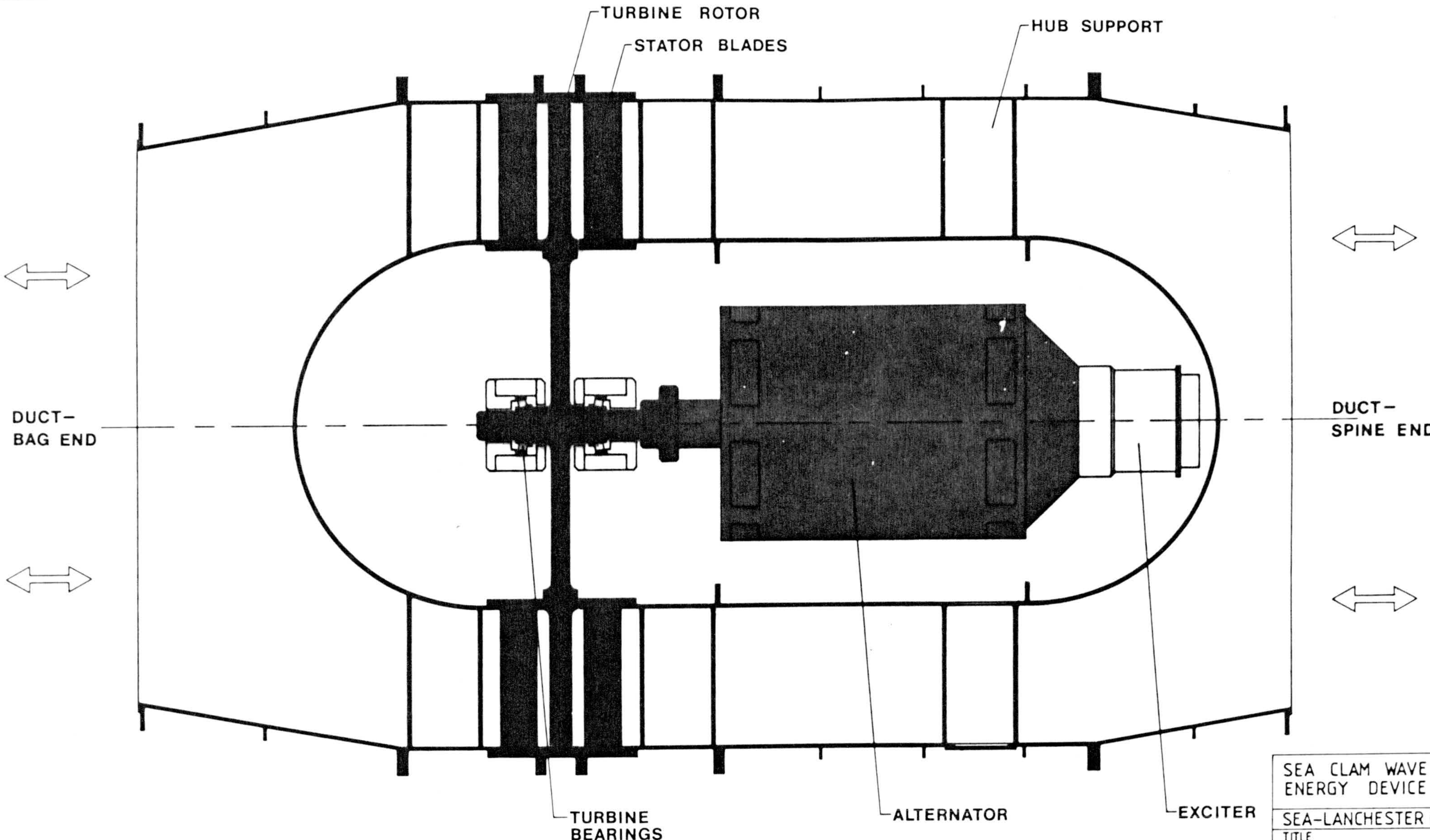

SEA CLAM WAVE ENERGY DEVICE

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TITLE

TURBO-GENERATOR MODULE

DRG N°

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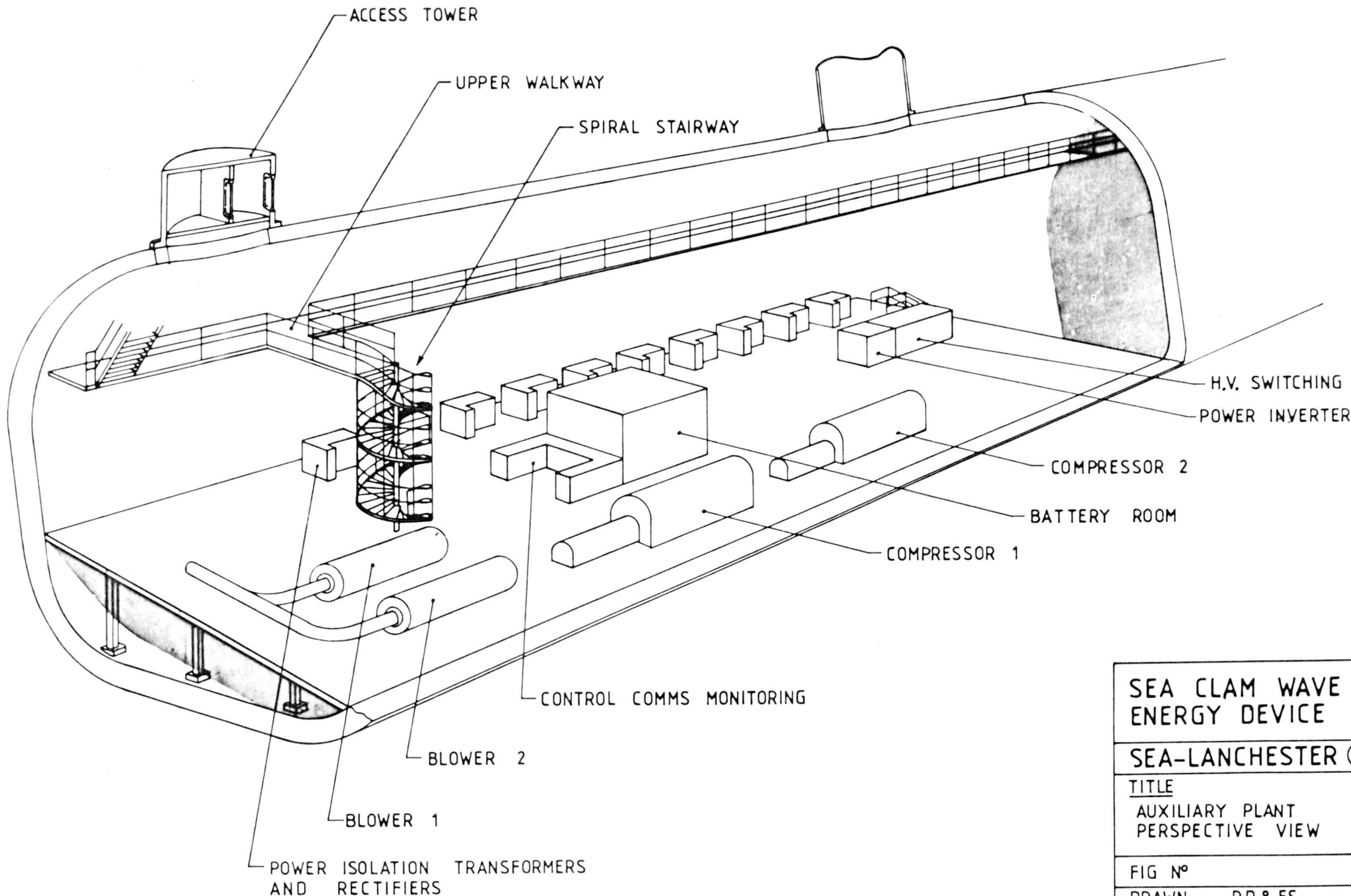
DATE OCTOBER 81



SEA CLAM WAVE ENERGY DEVICE

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TITLE

AUXILIARY PLANT PERSPECTIVE VIEW

FIG Nº

DRAWN RD & ES

DATE NOVEMBER 81

Seminar on

NEW ENERGY RESOURCES

Computational Mechanics Centre, Southampton,

19th-21st May,1981.

THE CLAM DEVICE

presented by N. W. Bellamy, B.Eng., Ph.D., F.I.E.E.

INTRODUCTION

After five years of research, the U.K. wave energy programme is nearing a point of decision on whether to progress towards full-scale testing or to continue on a research basis with reduced funding. The decision will be almost certainly based on the potential economics of wave energy and as a result, several device research teams are firming up on their designs prior to a cost assessment by consultants towards the end of this year. The chosen device or devices will probably have to produce electricity for the national grid at an estimated cost of less than 5 pence per unit at today's prices based on the costings of a 2 GW station located off the Outer Hebrides.

Sea Energy Associates Limited and the Coventry (Lanchester) Polytechnic have been involved in the national wave energy programme since 1975, first, on the 1/10th scale duck programme, (1, 2) and then more recently, on the second generation device known as the Clam (3). The Clam arose out of the need to reduce the high costs attributed to the first generation of wave energy devices and represented a new approach to the problem by an experienced team. By defining a simple concept which utilised components already identified as attractive, whilst at the same time avoiding known problem areas, the Clam quickly evolved into its 1979 design (3). This design has been tested at 1/50th scale in both natural and indoor waves with very satisfying results. Optimisation of the 1979 design has led to further design improvements which reduce the capital cost and increase the overall productivity. The final 1981 design should meet the cost criteria laid down and still retain some potential for further development.

This paper discusses the merits of the Clam device and reviews the progress to date.

THE CLAM WAVE ENERGY CONVERTER

The Clam can be classified as a spine-based pneumatic terminator. Devices utilising spines, that is long narrow structures, have been shown to be structurally efficient and, as such, featured in the three most cost effective devices in a 1979 assessment exercise. Of the three fluids available for wave energy conversion - air, water and oil - air is generally accepted as the most desirable. Closed circuit air is an additional advantage in that damage from water ingress is prevented. Terminator is the name given to devices which face, or nearly face, the wave front and extract the energy by terminating the wave in a matched load. Therefore , one can argue that a practical wave energy converter can be conceived as a floating spine terminator with a pneumatic wave absorbing front face.

Briefly, the Clam is based on the reversal of a simple concept normally used in the laboratory for efficient wave making. It comprises flaps hinged to a floating spine with air bags sandwiched between. Ocean waves dissipate their energy as they impinge on the flaps and move them in and out. This causes air in the bags to be forced through self-rectifying turbines into an enclosed duct running the length of the spine, allowing interchange of air between Clam elements. The ramdomness of sea wave patterns combined with the small inclination of the spine to the wave front allows phased operation of the Clam elements, enabling the spine to act as a stable reference body. Typically, a 15MW generator unit would feature ten Clam elements on a spine nearly 300m long moored to face the waves, as illustrated in Figure 1.

The cutaway view in Figure 1 shows the Clam spine with the flap, bag and turbine-generator equipment. Each Clam element has only two moving parts, the flap itself and the turbine-alternator rotor. It is the simplicity of this arrangement which enhances reliability and aids maintenance. The following paragraphs consider the design principles for each component part which are necessary to meet the system requirements.

The spine is a major structural component and accounts for about 20% of the capital costs. Its prime function is to act as a frame of reference in the form of a floating beam that is capable of withstanding wave-induced bending moments and hydrostatic loads. Both device productivity and cost increase with spine dimensions, and, as a result the optimum size of spine is not easy to calculate particularly when dealing with the random excitation of waves.

Each of the ten steel flaps is 30m long, 15m high and varies in width up to 1m. Along the bottom edge of each flap would be up to 60 individual hinges of the type used as rollers on the tracks of heavy earth moving equipment. It is the flap which has to extract the energy from the waves and couple its swepted displacement to the air in the flexible bag. Evans (4) has analysed the simple vertical hinged plate and confirms its efficient operation if it is tuned and damped correctly. Simple experiments in laboratory narrow tanks also demonstrate the broadband efficiency of a flap although air losses make it difficult to measure accurately the overall efficiency of a flap-bag combination at small scale. The flap is the most expensive component of the Clam and its elimination would be a major step forward. Development of the soft-fronted Clam will be discussed later.

The air bag is speculative in the sense that no fabrication for a similar duty exists. There is no doubt that bags can be manufactured from flexible fabric materials and would work for a reasonable period of time provided certain design rules were followed. The question is how long would a well designed bag last before fatigue or wear induced failure. Five years is considered satisfactory before replacement would have to be carried out during general refurbishing periods. However, it is likely that bag design will develop rapidly during the long commissioning stages of a large wave energy station and bag lifetimes of ten years or more may be achieved.

There are two types of air system which could convert the reversing air flow from each bag into a high speed uni-directional shaft drive for electrical generation. First, rectifying valves could be used to draw air from a low pressure duct and feed it to a high pressure duct to drive one larger turbine for the whole spine unit. This method would require large and reliable rectifying valves and also present a constant pressure load to the wave driven flap instead of the ideal linear damping. The second and more favoured air system is to use one self-rectifying air turbine at each bag orifice and interchange the air by means of a common duct running the full length of the spine. Self-rectifying turbines have some very desirable characteristics. They are simple, efficient over a broad power range, present a linear load and have a low drag loss when running free. The inherent inertia of the turbine generator units would make then essentially constant power-constant speed systems for a given sea state. Modular design would ensure low costs and easy construction, maintenance and replacement procedures.

The Clam has a unique 'close down' mode. By venting the pressurised air system, the flaps automatically close onto internal fenders under the pressure of external water head. Maintenance and inspection can then be carried out at sea with moving parts static. In the event of a malfunction, the device can be closed down partially or completely to limit progressive damage.

The mooring system follows the design used on the loch Ness duck tests and subsequent spine mooring trials. The proposed 2000MW scheme consists of a single line of 200 spine units, each 300m long and spaced at 400m centres. The front mooring for each spine comprises a single anchor point situated in 60m or more depth of water and connected to a leading buoy of 200 tonne displacement and then by two rodes to the spine in a V-yoke configuration. Rear restraining moorings allow the spines to swing through $\pm 40^{\circ}$ to face the principal wave direction. Piled rock anchors will have to be used at the majority of the wave power sites along the coast of the Hebrides.

Electrical transmission to land is dictated by the availability of high voltage flexible cables for connection to the sea bed. 35kV flexible single core d.c. cables can be used to give 200MW groups before transmission to land converters. Hence generator outputs on each spine unit will have to be transformed and rectified to give about 3kV d.c.

EFFICIENCY

The efficiency of the Clam device as a wave absorber can be derived theoretically using a suitable mathematical model or measured experimentally using scaled models in laboratory tanks and in natural waves. Both these methods of predicting the performance of a full scale Clam wave energy converter in the wave climate of a full season are rather limited. Mathematical models have to make many simplifying asssumptions in order to provide useful indications of the effect of design features on performance whereas experimental work at small scale is dominated by frictional losses and unrepresentative component behaviour. Even so, a great deal can be done with the present mathematical techniques available and considerable progress has been made towards an overall picture of the operation of the Clam.

If a linear mathematical model of the Clam is developed covering the hydrodynamic interaction of the Clam flap with the sea and the air flow between the bag and a fixed spine through the turbine, the following expression is derived -

$$\text{Efficiency} = \frac{|A^+|^2}{|A^+|^2 + |A^-|^2} \cdot \frac{4\ D\ D_A\ \omega^2}{(K-(I+I_A)\omega^2)^2 + \omega^2 (D+D_A)^2}$$

where A^+ and A^- are complex velocity potential amplitudes of the upstream and downstream radiated waves.

D and D_A are the turbine and added damping

K is the spring rate due to buoyancy and device design.

I and I_A are the device and added inertia.

The first term in the expression is the maximum possible device efficiency and depends solely on the external shape and mode of motion of the device. It is a measure of how successful a unidirection wavemaker the device is and underwrites the theory that good wave absorbers must be good wave makers. At high frequency $|A^-| << |A^+|$ and the potential efficiency is high and at low frequency $|A^-| \simeq |A^+|$ and the maximum efficiency reduces to 50%. Curve 1 in Figure 2 shows this maximum capture efficiency for the 15m deep Clam. The second term represents the extent to which the device is tuned and, for a given ω maximises to 1 when resonance is arranged and the damping rates are matched, that is

$$K = (I + I_A)\omega^2 \text{ and } D = D_A$$

Taking account of all the Clam dimension parameters of the 1979 design, the overall capture efficiency of the Clam is given by curve 2 in Figure 2, and indicates good resonance tuning.

To determine the performance of the Clam flap experimentally, a series of back to back tests were carried out whereby the overall transmission efficiency of a Clam type absorber mechanically coupled to a Clam type generator was measured. These tests used 1/100th and 1/50th scale models in a narrow tank and gave results very similar to the predicted theoretical efficiencies as shown by Curve 3 in Figure 2. Further tests of a flap-bag combination mounted on a special pneumatic test rig have confirmed these results for waves equivalent to 4m trough to crest at full scale.

The efficiency predictions so far have assumed a fixed spine to provide a perfect frame of reference. A freely floating spine, however, may be expected to move bodily to some extent in a given sea state and hence modify the overall performance of the device. To take account of spine movement the term 'spine efficiency' is defined which is taken to be 100% or less depending on the degree of spine motion although it could be argued that performance can be enhanced in certain conditions. Measurement of spine efficiency is difficult and can only be done on complete models with extensive instrumentation. Tests on the 1/50th scale Clam model at Draycote reservoir and in the Cadnam wide tank have demonstrated the remarkable stability of the spine and have provided data to produce the efficiency curve in Figure 3.

Overall device capture efficiency is the product of Clam efficiency and spine efficiency and has to be determined on an annual basis by considering all the sea states associated with the scatter diagram of the wave energy site in question. It has then to be multiplied by the power chain efficiency with due allowance for reliability which results in a rather low delivered power to the grid when compared with the resource available. Productivity of the Clam device was determined in the 1979 assessment exercise by consultants and is tabled here in comparison with the 1981 target figures.

Clam Productivity

	1979 Design	1981 Target
Available power (kW/m)	49.9	50.0
Directional factor	0.83	0.85
Capture efficiency	0.37	0.50
Digital corrections	0.93	0.95
Power chain efficiency	0.63	0.65
Power chain reliability	0.82	0.85
Delivered power (kW/m)	7.3	11.2
Maximum power (kW/m)	28.2	37.0
No. of spine units	236.0	200.0
Average annual output of a 2GW rated station	0.52GW	0.6GW

RECENT DEVELOPMENTS

A critical examination of the 1979 Clam design has been carried out over the past year and certain design improvements have been incorporated. Two obvious areas need attention. First, the flap is expensive and attracts engineering criticism because it is a large moving part and hence needs reducing in size or eliminating altogether. The idea of the soft-fronted Clam has always been attractive but difficulat to realise in practice. Secondly, the air ports into the spine interfere with the spine strength and create a flooding hazard in the event of bag failure. It would be more advantageous to have all spine orifices above water level where the air ports would be easier to protect from flooding and at the same time double up as machinery access points.

Figure 4 shows the Clam development towards the 1981 design which simplifies the design and reduces costs. Removal of the flap is made possible by the introduction of water into the bag to maintain the apparent Clam action of the front surface. The efficiency and air displacement is maintained in this arrangement but the front air orifice is unsatisfactory. Locating the orifice on the top of the rounded spine requires a flexible coupling into the bag to cater for the small relative movement between the rear top of the bag and the spine. Further developments of the 1981 design has led to more improvements which will be reported in due course.

Narrow tank tests on soft-fronted Clam designs have given very high efficiencies due to the elimination of the spring rate of the bag rolling against the flap and the flap inertia. Buoyancy spring rate is more of a problem than with the idealised Clam but careful design should tune this out with the added inertia. What is surprising is the tolerance of waves to mismatched movements of the absorbing surface where it seems only matched displacement is required to achieve the highest efficiency. This observation gives a large scope for bag design for soft-fronted clam arrangements.

This summer soft-fronted absorbers with simulated turbine dampers will be attached to the 1/10th scale spine at present on test in Loch Ness. Results from these tests should confirm the theoretical and experimental predictions of Clam performance and behaviour.

COST ESTIMATES

The large structures associated with wave energy converters naturally lead to high capital costs. Any high technology components can add significantly to the basic structure costs through maintenance and reliability problems. The Clam is designed as a simple structure with the minimum of high technology components. Operating costs should be low between the five year refurbishing periods when component parts will be repaired or replaced.

The final 1979 UK assessment exercise derived the following costs for one Clam spine unit. The 1981 target figures are also tabled for comparison purposes.

Clam Costs (£M at Nov '79 prices)

	1979 Design	1981 Target
Spine structure	2.18	2.0
Flap	2.64	-
Bag	0.60	0.80
Power plant	2.40	2.0
Moorings	1.12	1.0
Transmission	1.97	2.0
Sundries	0.65	0.5
Contingency (10%)	1.14	0.9
TOTAL	12.7	9.2

From these capital costs and the productivity figures given earlier, the cost of power can be calculated using accepted interest charges and maintenance and running costs.

Cost of Power (At Nov '79 prices)

	1979 Design	1981 Target
Cost of each device (£M)	12.7	9.2
No of devices for 2GW	236	200
Total capital cost (£M)	3000	1840
Annual cost at 7.1% interest (£M)	213	130
Annual maintenance at 3% (£M)	90	55
Total annual cost (£M)	303	185
Mean annual output (GW)	0.52	0.6
Cost of power (p/kWh)	6.6	3.5

Te 1981 target figure for the cost of power is within the likely 5p per unit criteria even with the inflation since 1979. It is dangerous to quote the conventional costs of generating electricity but they must bracket the wave energy figure when costed on the same basis. A five year development period from scratch of a new technology is not a long time when compared with the many life cycles of its competitors.

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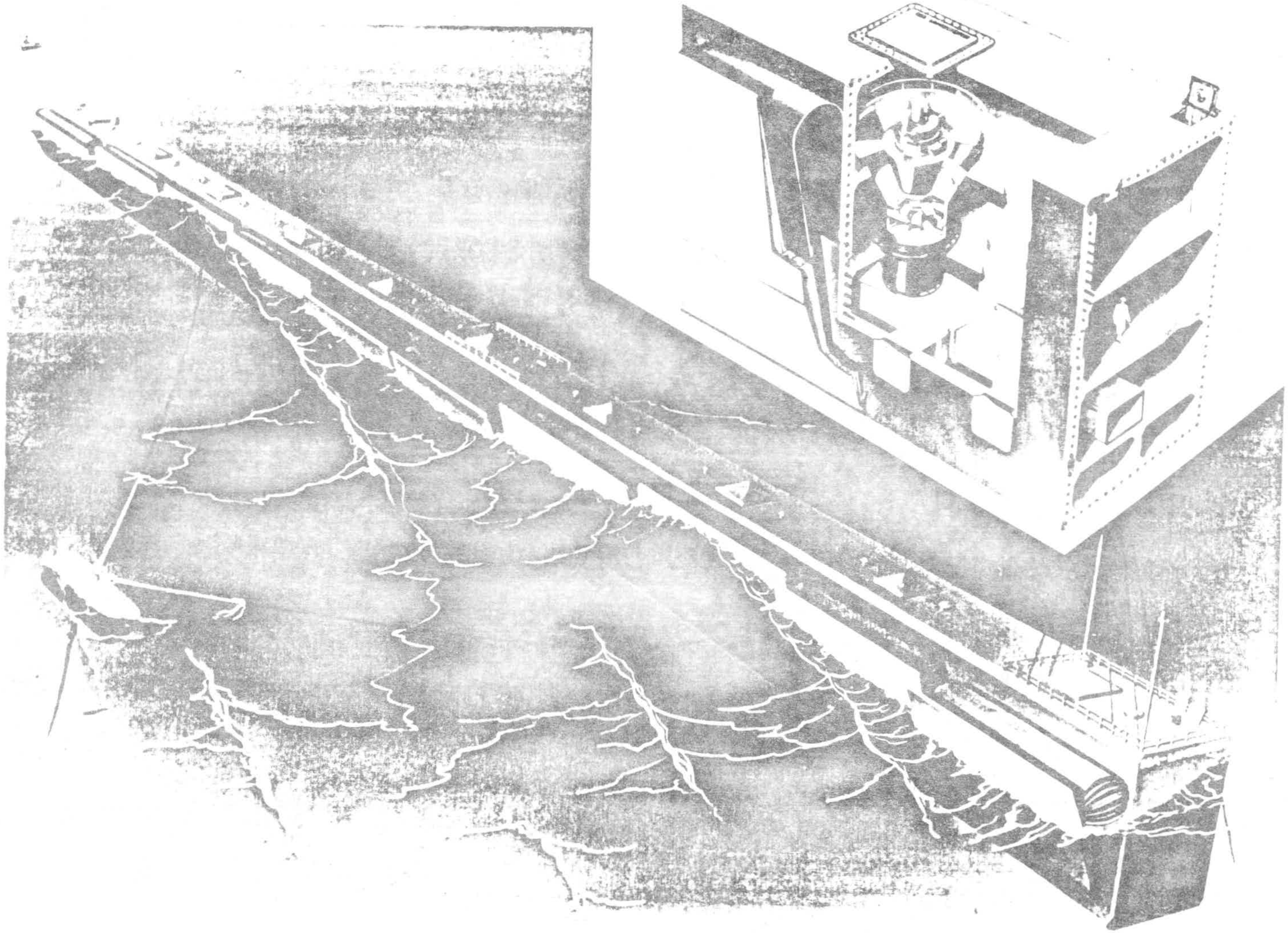


FIGURE 1

Artist's impression of the Clam Wave Energy Converter with cutaway view showing flap, air bag and turbine equipment.

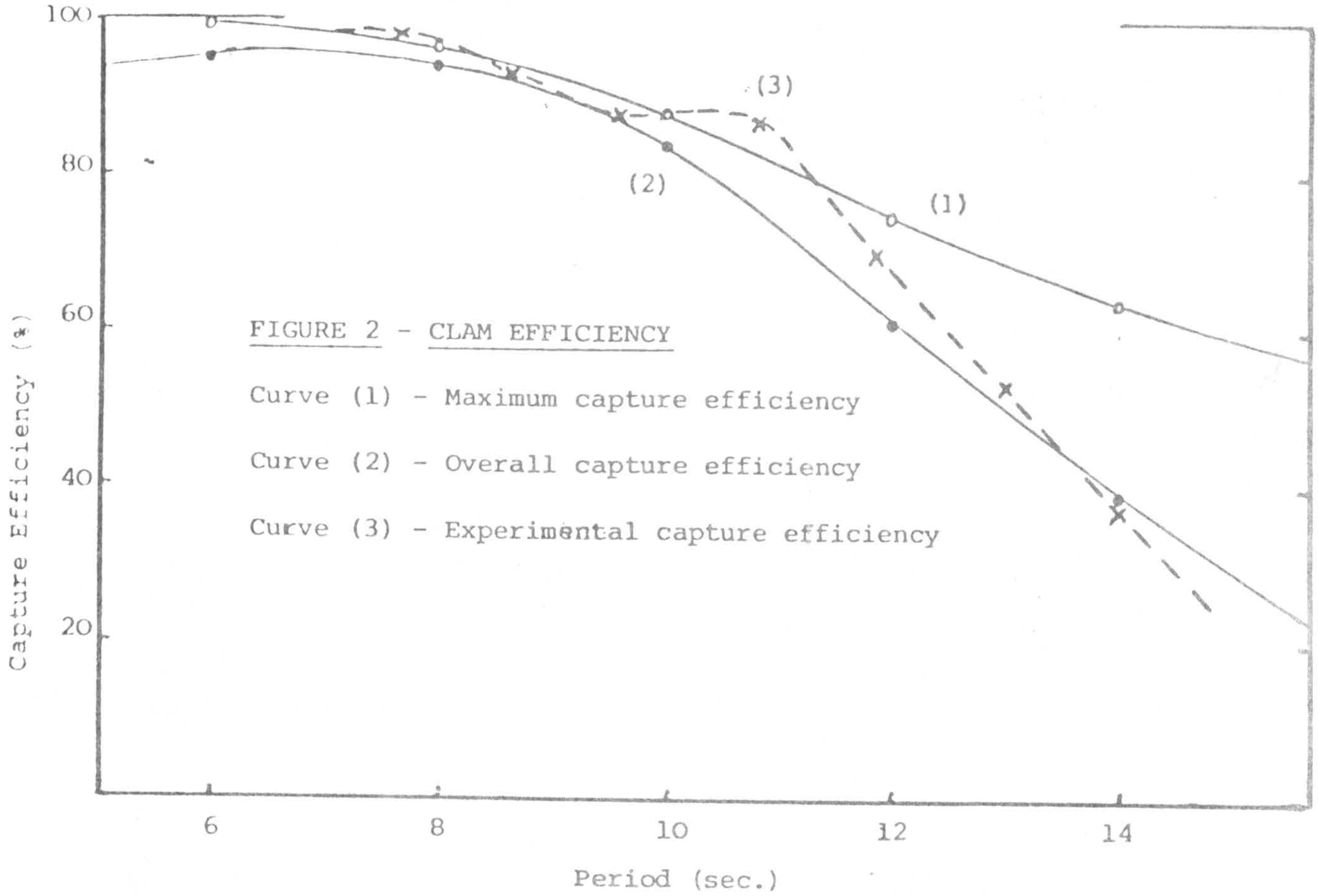


FIGURE 2 - CLAM EFFICIENCY

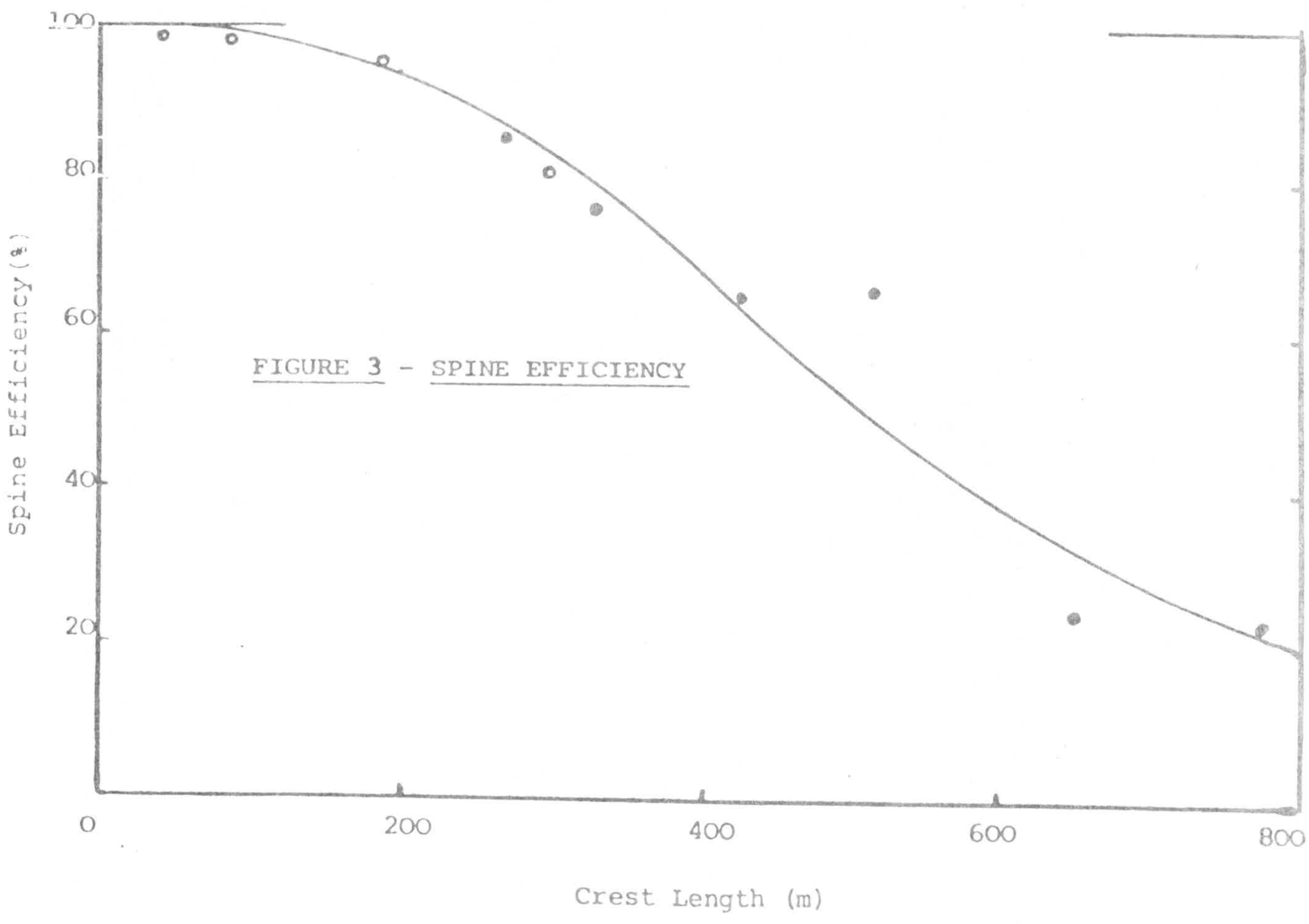
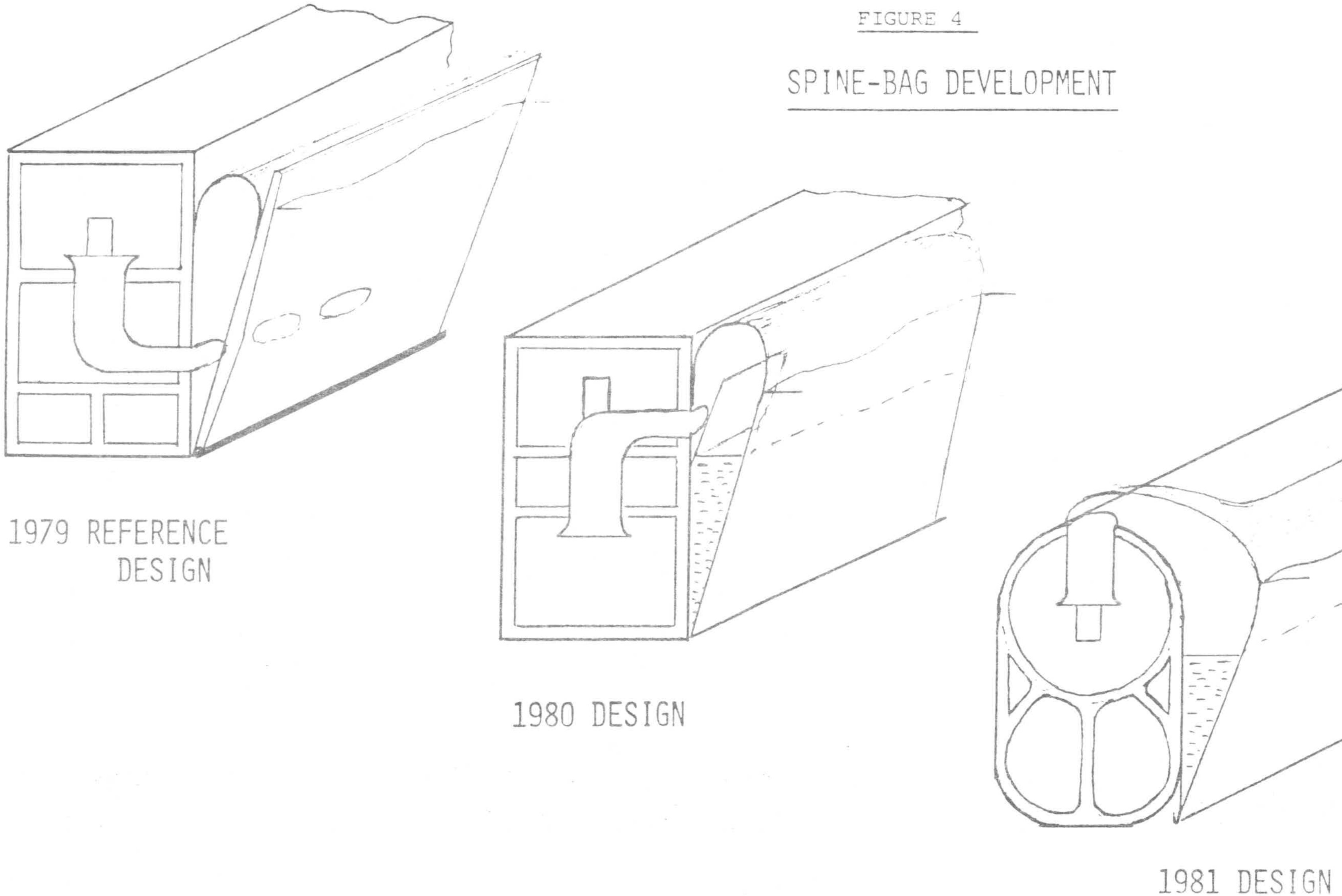
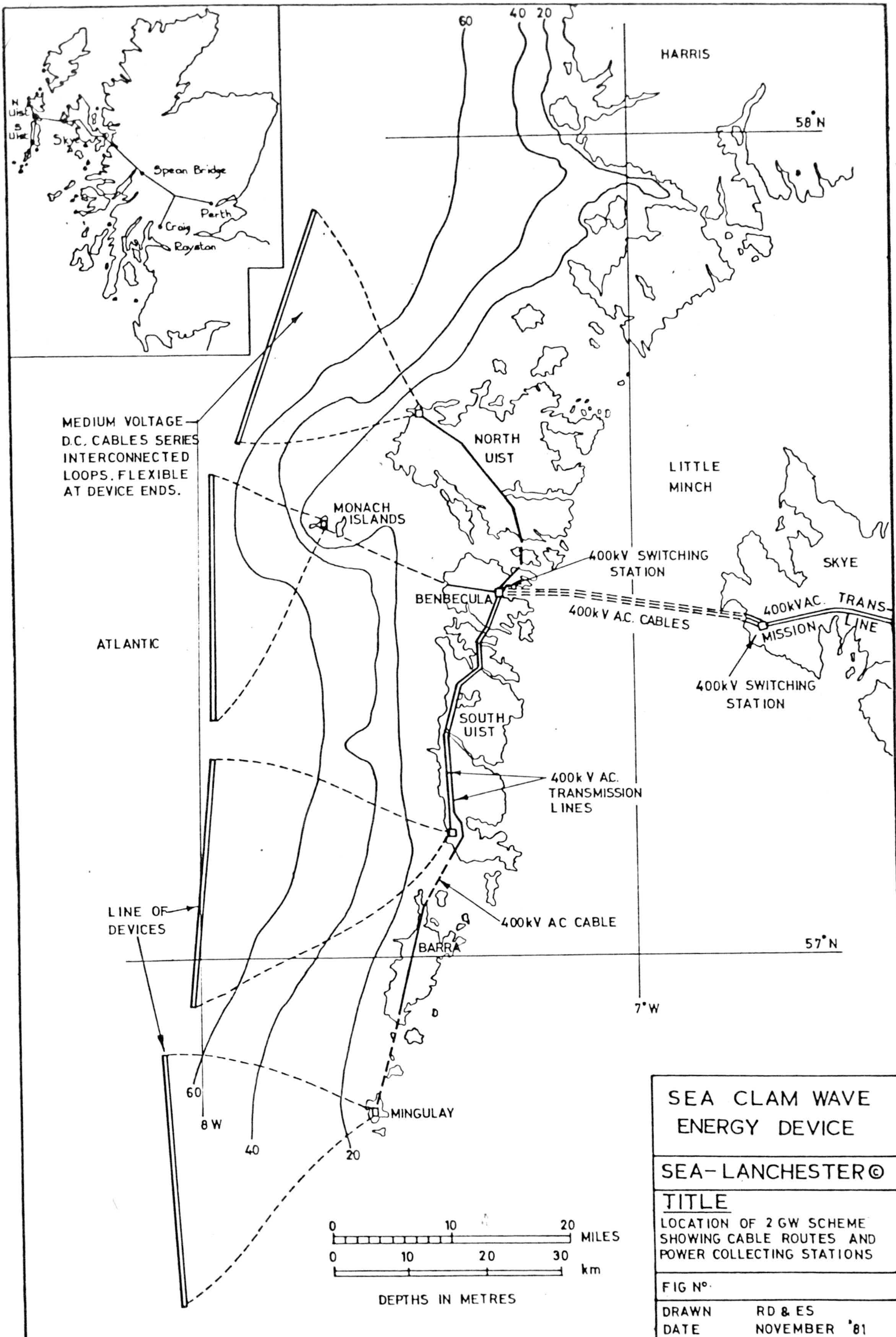


FIGURE 3 - SPINE EFFICIENCY

FIGURE 4

SPINE-BAG DEVELOPMENT

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S Uist
Skye
Spean Bridge
Perth
Craig
Royston
HARRIS
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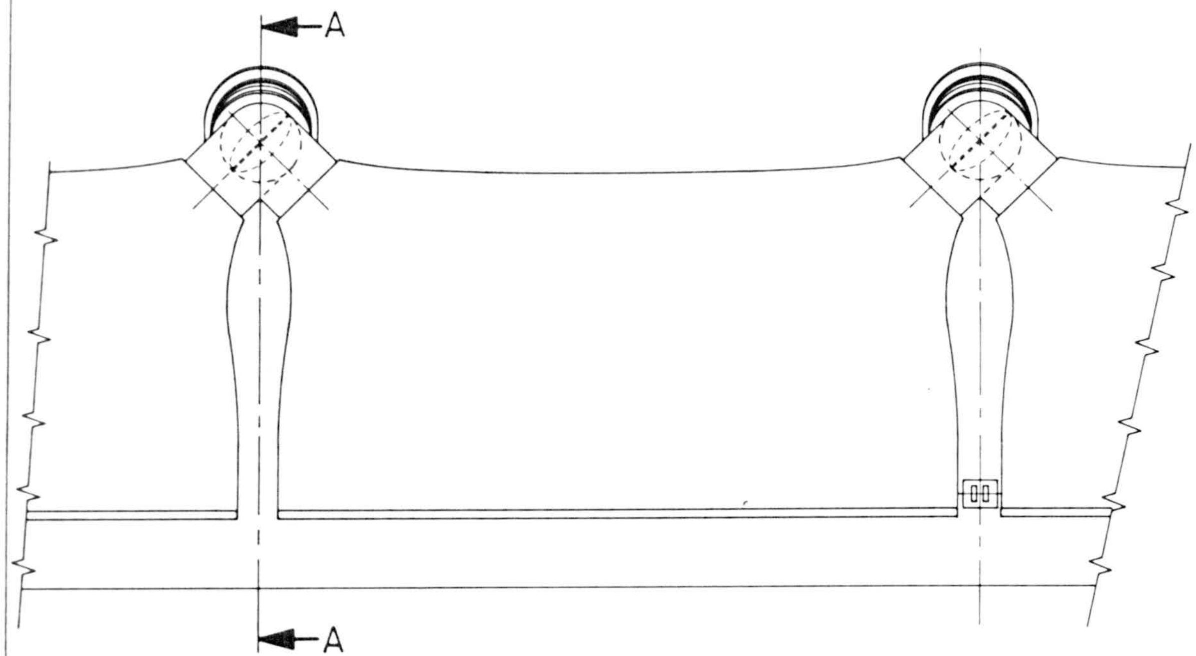
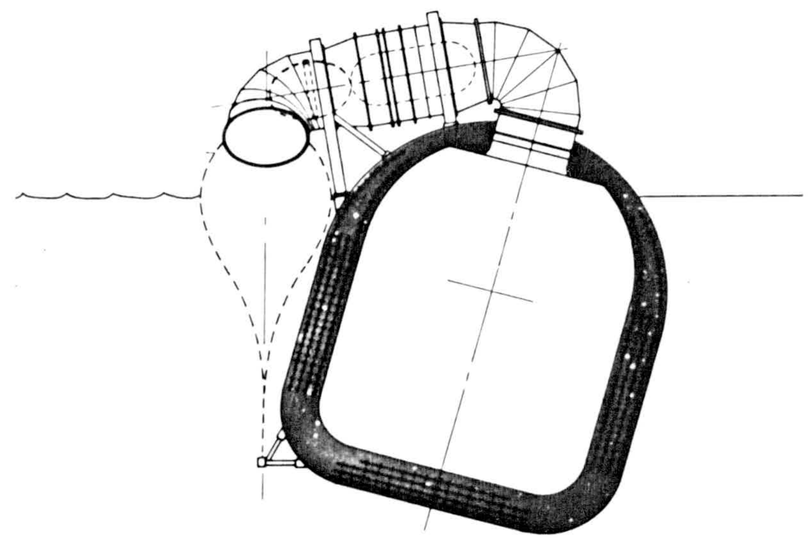
MEDIUM VOLTAGE D.C. CABLES SERIES INTERCONNECTED LOOPS. FLEXIBLE AT DEVICE ENDS.
NORTH UIST
LITTLE MINCH
MONACH ISLANDS
400kV SWITCHING STATION
BENBECULA
400kV A.C. CABLES
400kVAC. TRANSMISSION LINE
SKYE
400kV SWITCHING STATION
ATLANTIC
SOUTH UIST
400kV AC. TRANSMISSION LINES
LINE OF DEVICES
400kV AC CABLE
BARRA
57°N
7°W
60
8 W
40
20
MINGULAY
0 10 20 MILES
0 10 20 30 km
DEPTHS IN METRES
SEA CLAM WAVE ENERGY DEVICE
SEA-LANCHESTER©
TITLE
LOCATION OF 2 GW SCHEME SHOWING CABLE ROUTES AND POWER COLLECTING STATIONS
FIG N°.
DRAWN RD & ES
DATE NOVEMBER '81





SECTION AA

SCALE 1:100

SEA CLAM WAVE ENERGY DEVICE

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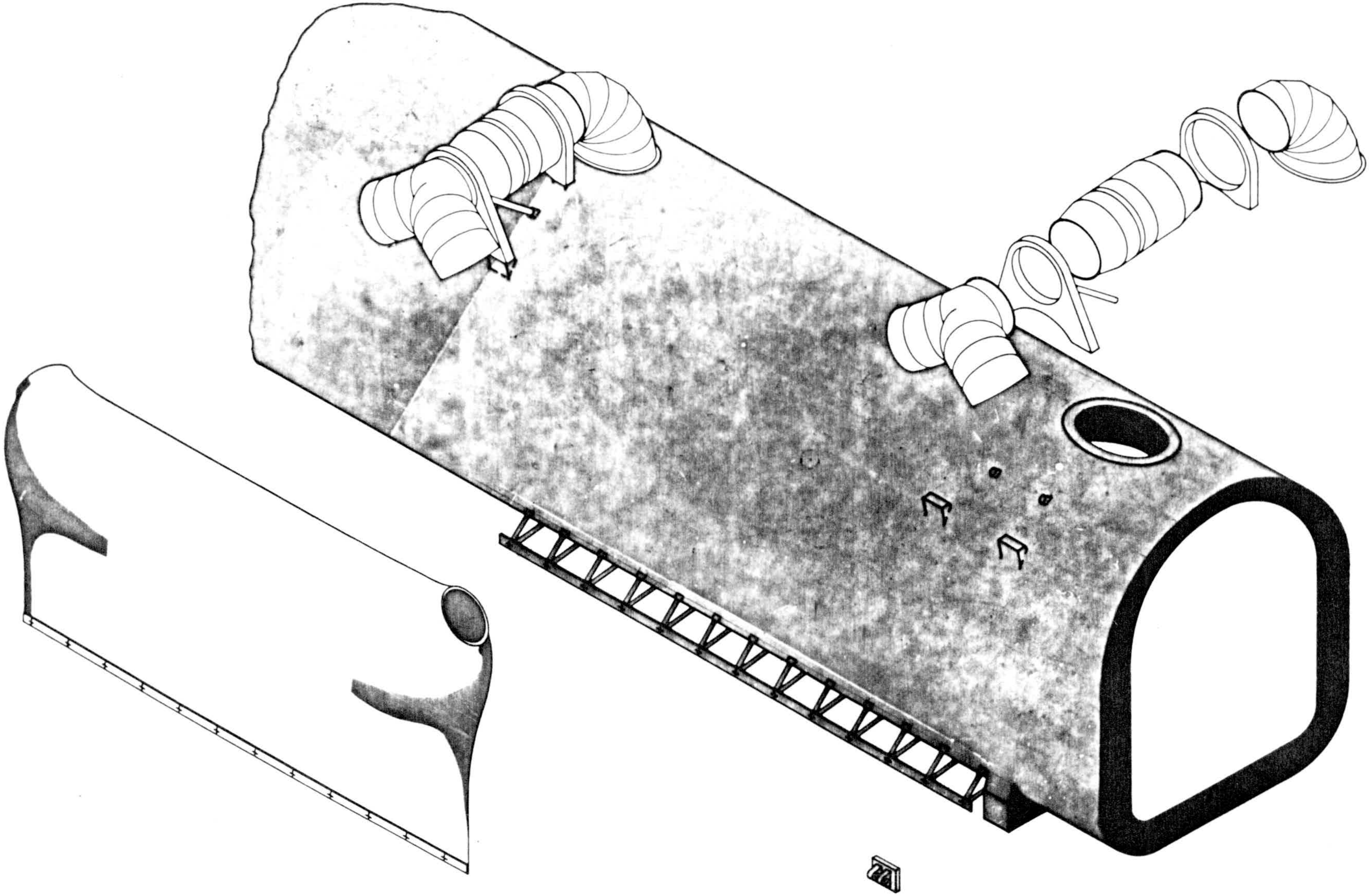
TITLE

GENERAL ARRANGEMENT

DRG Nº

DRAWN RD&ES

DATE OCTOBER 81



SEA CLAM WAVE ENERGY DEVICE

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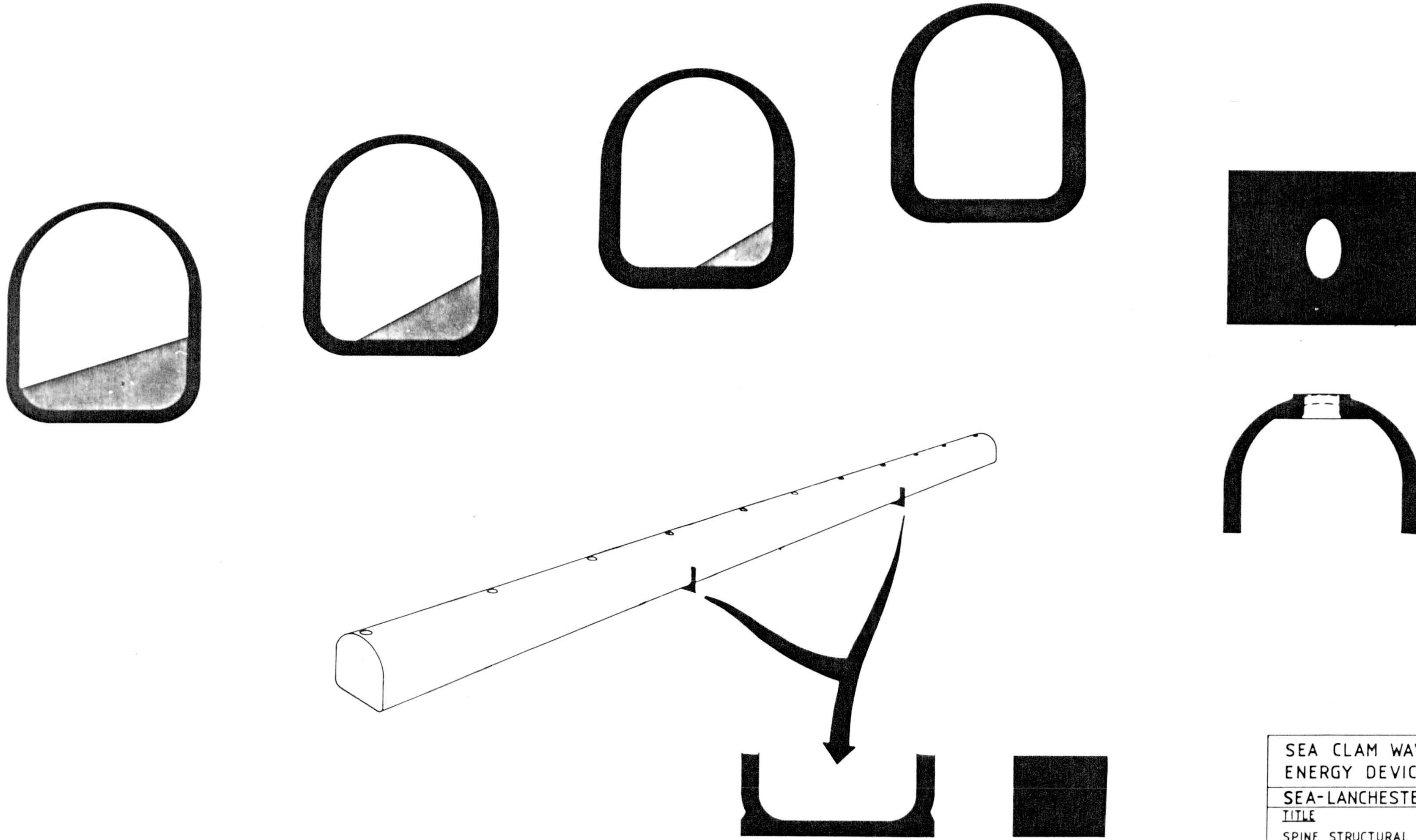
TITLE

PRINCIPAL COMPONENT PARTS

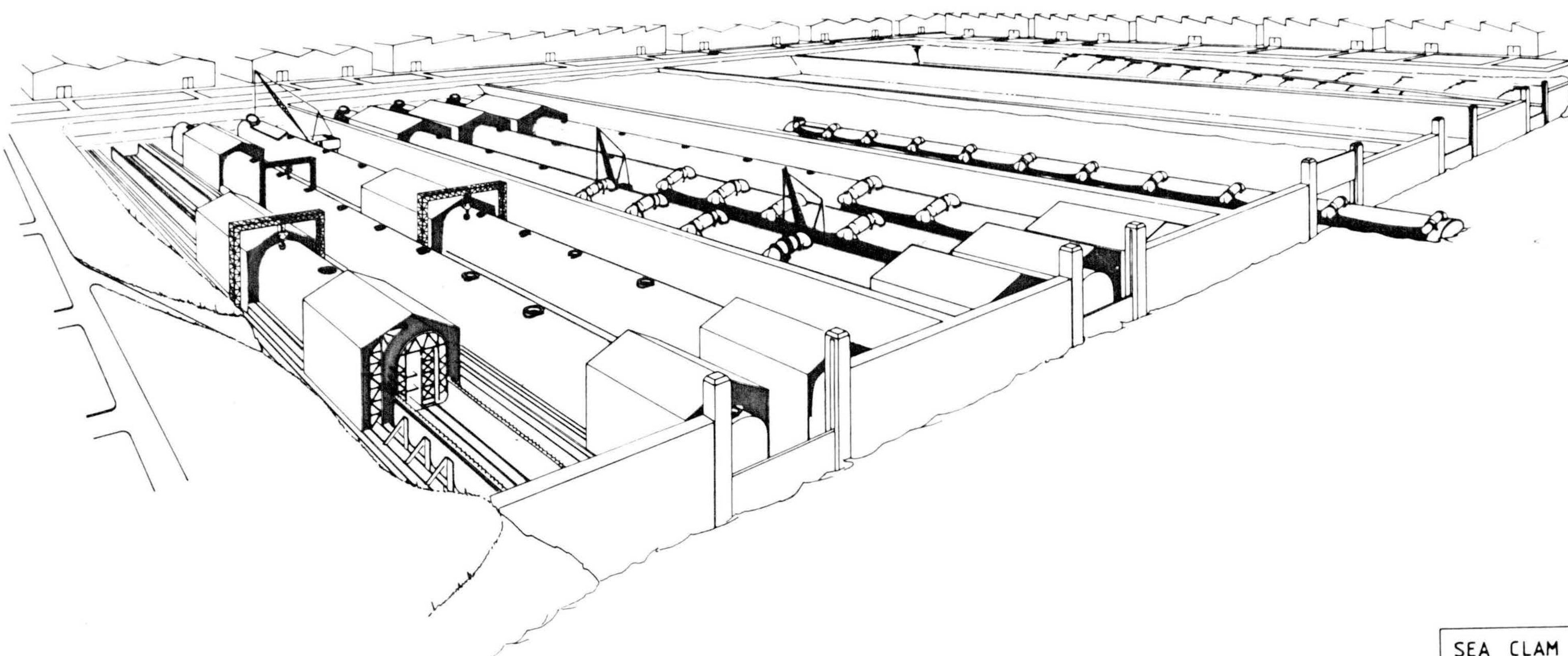
DRG Nº

DRAWN RD & ES

DATE DECEMBER '81



SEA CLAM WAVE ENERGY DEVICE
SEA-LANCHESTER ©
TITLE SPINE STRUCTURAL CROSS SECTIONS
DRG Nº
DRAWN. RD & ES DATE DECEMBER '81



SEA CLAM WAVE ENERGY DEVICE	
SEA-LANCHESTER ©	
TITLE	
CONSTRUCTION FACILITY	
DRG N°	
DRAWN	RD & ES
DATE	DECEMBER 81